

Learning from errors: A model of individual processes

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Article received 4 May / revised 16 October / accepted 2 March / available online 6 April

Abstract

Errors bear the potential to improve knowledge acquisition, provided that learners are able to deal with them in an adaptive and reflexive manner. However, learners experience a host of different—often impeding or maladaptive—emotional and motivational states in the face of academic errors. Research has made few attempts to develop a theory that focuses on learning from errors (with the exceptions of the theory of impasse-driven learning and the theory of negative knowledge) and, in particular, a theoretical framework that focuses on antecedent motivational processes. By integrating theories of self-regulated learning, volition, attributions, and appraisals, we propose a model that highlights individual processes that are characteristic of this specific learning phenomenon. More precisely, our theoretical framework aims to explain how emotional, motivational and self-regulatory processes— influenced by personal and contextual conditions— interact in order to facilitate or impede adaptive dealing with errors and appropriate metacognitions and cognitive activities. Our objective is to provide a framework that allows for the systematic integration of various aspects that have been targeted in previous research and to guide and stimulate future research on learning from errors. As a first evidence for validation, we summarise research findings that address specific parts of the proposed model.

Keywords: Learning from errors; self-regulation; motivation; emotion



1. Learning from errors: A specific learning phenomenon

In order to facilitate learning—the development of knowledge, metacognitive skills and autonomy—learners should be challenged with tasks that refer to skills and knowledge just beyond their current level of mastery (Vygotsky, 1978). Errors are a natural by-product of attempting challenging learning tasks and they may, in particular, provide learning opportunities (Van Lehn, 1988). Recent research findings in educational psychology and contemporary cognitive psychology (e.g. Cyr & Anderson, 2014; Van Lehn, Siler, Murray, Yamauchi, & Baggett, 2003) give reason to revisit ancient wisdoms like “Mistakes are the stepping stones for learning” or “You can always learn from your mistakes”. Based on empirical findings, the consistent key argument is that errors initiate explanation and reflection processes in which deficient concepts are contrasted with correct concepts in order to establish accurate mental models (see also Chi, 1996; Kapur, 2008; Oser & Spychiger, 2005; Siegler, 2002). However, as Van Lehn et al. (2003) put it, “a learning opportunity is only an *opportunity to learn*”. Accordingly, empirical findings consistently point to the importance of metacognitive support (e.g. Keith & Frese, 2005; Künsting, Kempf, & Wirth, 2013). For example, Westermann and Rummel (2012) found that metacognitive support during student collaboration on difficult learning content and discussions of their wrong solutions lead to better learning outcomes. In addition to metacognitive processes, *motivational processes* obviously play a particularly important role for successful learning from errors. Experiences of errors and impasses are accompanied by a host of different emotional and motivational states which facilitate or impede persistent learning engagement, the use of appropriate metacognitions, and cognitive activities. It can be assumed that poor learners are characterised by the experience of deactivating emotions following errors (for more details see section 2) and an inability to regulate their motivation and the respective emotions adaptively. In other words—as with learning in general (cf. Kanfer & Ackerman, 1989) but particularly after making errors—learning from one’s own errors through (self-) explanation basically requires motivational forces in order to persist after setbacks, to correct the error at hand, and to reflect on the underlying misconceptions.

Surprisingly, educational research has paid little attention to learning from errors. A theoretical framework that addresses error-related learning *processes* in terms of emotional experiences, motivational changes, self-regulation, metacognitive activities, and cognitions is lacking. In order to explain why some learners show adaptive reactions and learning gains after errors while others fail to do so, such a model needs to simultaneously explain individual differences with motivational self-regulatory processes (inextricably bound to emotions) as well as the learners’ prerequisites and conditions (i.e. dispositions, motivational beliefs and orientations, knowledge, abilities or skills) in interaction with characteristics of the learning environment and the context. We propose a model with perceived errors as the events that initiate self-regulation. It systematically integrates personal determinants, contextual conditions and situational processes that are specific for learners dealing with errors. Within this framework, we integrated components of previous models and built on the central assumptions of established theories (for another attempt to integrate different motivational theories, but not specifically adjusted to processes following errors, see De Brabander & Martens, 2014). In particular, we included models that contribute to explain individual processes following errors—all of them further addressed in the next sections: the transactional stress/coping model based on primary and secondary appraisals (Lazarus & Folkman, 1984), aspects of volition theory (Kuhl, 1985, 2000), feedback loops (Carver & Scheier, 1998), self-regulation models (Boekaerts, 2006; Winne & Hadwin, 1998) and theories of impasse or error-driven learning (De Leeuw & Chi, 2003; Kolodner, 1983, 1997; Minsky, 1997; Oser & Spychiger, 2005; Van Lehn, 1988). Findings from studies on error management (Heimbeck, Frese, Sonnentag, & Keith, 2003; Keith & Frese, 2005) and error-related beliefs or attitudes (Rybowski, Garst, Frese & Batinic, 1999; Tulis & Ainley, 2011; Tulis, Steuer & Dresel, subm.) complete our proposed model.



1.1 Current state of research

Within the behaviouristic paradigm, and for a long time in the field of cognitive psychology, it was assumed that errors should be avoided because they would interfere with correct information and thus hinder the recall of correct answers (e.g. Ayers & Reder, 1998). In contrast, contemporary research provides empirical evidence for the fundamental role of errors in learning: Overcoming impasses through reflection on errors and (self-) explanation of the underlying misconceptions has been shown to be important for learning progress since these processes help to establish accurate mental models (Kapur 2008; Mathan & Koedinger, 2005; Oser & Spychiger, 2005; Siegler, 2002; Van Lehn et al., 2003). Based on a comprehensive literature review, we found different approaches that have been adopted in educational research to investigate the role of errors in learning: Alongside research on classroom error management and error climate (e.g. Tulis, 2013; Steuer, Rosentritt-Brunn & Dresel, 2013), individual responses to errors have been examined under different perspectives: For instance, there is a large body of research on (error) feedback and its impact on learning and achievement (for a meta-analysis see Bangert-Drowns, Kulik, Kulik & Morgan, 1991; for an overview see Mory, 1996).

However, most of these studies did not address learning from errors per se. Going deeper into this issue, a line of research has investigated students' error patterns from a diagnostic perspective (for mathematics: Clements, 1980; Fiori & Zuccheri, 2005; Resnick, 1984) and has elaborated on error-types and taxonomies (e.g. Frese & Zapf, 1994). More recent studies have focused on learning from erroneous examples (Eichelmann, Narciss & Schnaubert, 2013; Große & Renkl, 2007). For example, Große and Renkl (2007) found that incorrect solutions lead to enhanced learning outcomes if learners have favourable prior knowledge. Including errors in worked examples motivated these learners to explain what was wrong and why, and it fostered elaborations on the correct solutions. Their results underpin the positive relationship between transfer performance and the generation of self-explanations when learning with incorrect solutions. Other researchers have concentrated on learning from errors with (intelligent) tutors (Mathan & Koedinger, 2005; Van Lehn et al., 2003). Mathan and Koedinger (2005) focused on learners' error-detection and error-correction skills and how these can be supported. The authors provide evidence that feedback which allows students to detect, correct and reflect on their own errors fosters learning at a faster rate, conceptual understanding, and (transfer) performance. Similarly, but in another setting (i.e. collaborative learning environments), research on productive failure has emphasised the benefits of delaying instruction in order to enable reflection on incorrect solution attempts by students (Kapur, 2008; Westermann & Rummel, 2012). Van Lehn and colleagues (2003) investigated the conditions of successful learning episodes within their framework of impasse-driven learning. In particular, they studied tutorial dialogues between students and expert tutors. The results suggest that impasses and errors are strongly associated with learning. Reaching impasses and clarifying errors turned out to have stronger effects on effective learning than when a tutor modelled the correct action. Finally, some researchers have addressed learners' attitudes towards making errors (Rybowski et al., 1999) and implemented the positive function of errors for learning in a training condition (Gully, Payne, Koles & Whiteman, 2002; Kanfer & Ackerman, 1996; Keith & Frese, 2005). In these studies, the positive function of errors was prompted to participants while practising a task and the participants were encouraged to make errors. However, error-trainings had better effects on performance if they were combined with instructions providing metacognitive techniques supporting cognitive and emotional self-regulation (Keith & Frese, 2005) or if individuals were higher in ability, higher in openness to experience, or lower in conscientiousness (Gully et al., 2002).

In summary, there is a growing research interest in the specific phenomenon "learning from errors, but a theoretical framework that allows an integration of these different perspectives is lacking. In addition to the above-outlined findings regarding the individual preconditions and their interaction with training efforts to enhance successful learning from errors, learners' adaptive reactions to errors—their antecedents and consequences—have been considered to a minor degree. Particularly little attention has been paid to differences in learners' emotional and motivational responses to errors and their significance for subsequent learning processes. In this regard, we present four different theoretical perspectives on dealing with errors in



learning contexts in the following sections. Their theoretical assumptions build the basis for our proposed model described afterwards.

1.2 Perspectives on individual dealing with errors

A first perspective to explain individual differences in learners' reactions to errors can be derived from research on stress and coping (cf. Boekaerts, 2010). Lazarus and Folkman (1984) proposed two cognitive appraisal processes which determine if a situation is perceived as stressful. First, in a primary appraisal process an (error) situation is interpreted along a continuum ranging from irrelevant, benign-positive, not harmful to challenging, threatening or harmful. The secondary appraisal process further evaluates the situation and determines which coping resources are available and whether the individual can apply them effectively. Finally, the situation and coping strategies are monitored and evaluated, and the primary and secondary appraisals are modified if necessary. Numerous studies have shown that appraisal processes—operating automatically or conscious and volitional—determine emotional experiences (Lazarus, 1991). Altogether, appraisal theory appears to constitute a proper basis for describing emotional states, motivational changes and self-regulatory processes following errors.

A second perspective that is strongly related to learners' reactions to errors stems from research on reactions to (success and) *failure*. Literature review reveals an impressive body of research that has been proven to explain differences in individuals' (affective) reactions to failure based on different theoretical foundations (for an overview see Elliot & Dweck, 2005), such as achievement goal theory (for an overview see Maehr & Zusho, 2009), or attribution theory (Weiner, 1986). For example, mastery-oriented students with a focus on skill development and individual improvement do not necessarily feel threatened by failure when faced with a difficult task, but rather perceive setbacks as an opportunity for learning and mastery (e.g. Dweck & Leggett, 1988). Causal beliefs of the importance of effort for success were found to mediate the relationship between mastery orientation and retained positive affect after errors were made (Tulis & Ainley, 2011). In contrast, performance avoidance goals have been shown to be associated with increased negative affect following failure experiences and lower preference for difficult tasks (e.g. Elliott & Dweck, 1988). Clifford's (1984) theory of constructive failure also emphasised learners' differences in affective experiences following errors: Students who are focused on the task rather than on themselves were less likely to fear failure and to feel negative emotions. Rather, they were more likely to invoke positive thoughts and further appraisals of "challenge" (cf. Boekaerts, 1993). Finally, volition theory (Kuhl, 1985, 2000) has broached the issue of the interplay between emotion, motivation, metacognition, and cognition in the face of failure: Besides cognitive control—in terms of metacognitive activities directed towards keeping attention and effort on the task—emotion and motivation control (i.e. self-regulatory processes to keep negative emotions and other intrusive thoughts at bay during task engagement) can be assumed to mediate the effectiveness of learning from errors. In the context of learning situations, empirical studies by Kanfer and Ackerman (1996) provide evidence that emotion control is most critical when the task is likely to appear most daunting to the learner—a likely situation after making errors. Important to note is that, although failure and errors are interrelated constructs, they are not the same: Errors are usually defined as an unintended discrepancy between a current and a desired state, or as a deviation from a given standard (e.g. Frese & Zapf, 1994). "Failure" implies more than just this perceived discrepancy. In contrast to errors, failure experiences constitute a more global miss of a goal with a greater focus on the subsequent consequences (cf. Zhao & Olivera, 2006). Above all, not every error is necessarily interpreted as failure. Whether an error is evaluated as failure or not depends on situational aspects (e.g. social norms) and personal characteristics of the learner, such as self-concept of ability. Bandura (1997), as well as Eccles and her colleagues (e.g. Eccles & Wigfield, 2002), concluded that efficacy expectations or perceptions of self-competence are a major determinant of a person's willingness to invest more effort if the task becomes challenging—hence, also following errors.

Thirdly, regarding theories on learning from errors in a narrower sense, a perspective on dealing with errors stems from organisational psychology and technology based learning. Within the field of organisational psychology, rather economised working models developed for empirical studies in the field of



workplace learning have been proposed (Zhao, 2011; Bauer, Gartmeier, & Harteis, 2012; Van Dyck, Van Hooft, De Gilder, & Liesveld, 2010). Researchers have either primarily focused on personal characteristics that may facilitate or impede effective learning from errors at work (e.g. components of an error specific attitude, Rybowiak et al., 1999) or they have focused exclusively on contextual features, such as the organisational error climate. As an exception, Oser and colleagues (e.g. Oser & Spychiger, 2005) introduced the concept of “negative knowledge” (cf. Minsky, 1997) in the context of academic learning. It represents knowledge about false facts and inappropriate action strategies that labels incorrect concepts as wrong and helps to prevent the repetition of errors in similar situations. Similarly, Kolodner (1983, 1997) emphasised that individuals use knowledge about formerly experienced errors in new situations. Comparably, Van Lehn (1988) suggested that impasses pave the way for learning from the subsequent explanation and therefore are even necessary for learning processes. However, these theoretical explanations primarily consider cognitive processes, and they do not cover emotional, motivational, and self-regulatory *processes* following errors as antecedents of successful learning from errors.

In order to bridge this gap, contemporary models of self-regulated learning which propose recursive processes including emotional/motivational functioning as well as metacognitions and cognitive activities (e.g. Boekaerts, 1999; Pintrich, 2000; Schmitz, 2001; Zimmerman, 2008) appear to constitute a fourth perspective on differences in learners’ reactions to errors. More specifically, we explicate three self-regulation models in the following which provide a proper basis for describing motivational and self-regulatory processes following errors with different focal points (Boekaerts & Niemivirta, 2000; Carver & Scheier, 1998; Winne & Hadwin, 1998).

First, the “dual processing self-regulation model” (Boekaerts & Niemivirta, 2000; Boekaerts, 2006) provides a framework addressing the importance of affective experiences and the learners’ competences to regulate their emotions and motivation following errors. Two main goal priorities which are pursued by self-regulative activities are distinguished: (1) the “mastery/growth pathway” and (2) the “well-being pathway”. Learners who want to reach a specific subgoal in order to improve skills or gain knowledge (e.g. analyse the causes of the error at hand) initiate activities in the mastery/growth pathway because they value that goal and feel competent enough to commit energy to its pursuit. On the other hand, learners who are primarily concerned with the anticipated threat to their self-worth and the negative consequences of errors initiate activities in the well-being pathway. Importantly, it is assumed that learners can switch to the mastery/growth pathway by using adaptive emotional and motivational regulation strategies (Boekaerts, 2006).

Another theoretical model that can be used to explain both learners’ emotional as well as behavioural changes following errors was introduced by Carver and Scheier (1998). The authors have focused on the role of feedback control processes during self-regulation. The core construct in their model is a discrepancy-reducing feedback loop (or a discrepancy-enlarging loop in the case of an avoidance situation): If a discrepancy between a current state/situation (input function) and a goal/standard (reference value) is detected, adjustments are made in an output function in terms of behavioural changes. For example, a learner may invest more effort to identify the error causes or she may seek further information in the learning material after the perception of an error. Parallel to this behaviour-guiding loop, Carver and Scheier (1998) described the affect-creating feedback loop which operates automatically and simultaneously. It is assumed to monitor the rate of progress of behaviour discrepancy reduction over time. Hence, the theoretical model of Carver and Scheier (1998, 2013) provides an appropriate framework for behavioural reactions as well as the origins and functions of emotions that are experienced after errors.

Finally, the model suggested by Winne and Hadwin (1998) highlights the ongoing evaluation of potential discrepancies between products and standards of the learning process. In their model, the authors describe four basic phases—task definition, goal setting and planning, studying tactics, and adaptations to metacognition (for an overview see also Perry & Winne, 2006)—in terms of the interaction of personal and contextual conditions, products (i.e. learning behaviour and outcomes) compared with standards (i.e. the optimal end state of each phase) and the learner’s goals through metacognitive evaluation processes. All these



aspects are types of information that are used or generated during learning. A mismatch between products and standards is assumed to initiate further learning operations, the use of metacognitive strategies and/or the revision of the conditions and standards. The output, or performance, is the result of recursive processes that cascade back and forth, altering conditions, standards, operations, and products as needed. Thus, the model represents a “recursive, weakly sequenced system” (Winne & Hadwin, 1998, p. 281) and it primarily addresses cognitive and metacognitive activities. Therefore, it perfectly augments the proposed theoretical framework for learning from errors presented in the next section, which considers not only emotional and motivational but also cognitive and metacognitive processes and learning activities.

In summary, most of the theories outlined above focus on self-regulatory processes in general, but a sufficiently elaborated model with respect to perceived errors as initiating points for self-regulation is lacking. Previous research was not able to adequately explain individual differences in *error-specific* emotional and motivational self-regulation. Regarding prior research that aimed to investigate learning from errors, it is striking that self-regulatory processes—in particular motivational processes—have only been addressed sketchily, although there is a common agreement on their importance in the face of setbacks. A theoretical perspective for relating personal and contextual conditions and motivational (self-regulatory) processes following errors is needed to explain and systematically investigate error-related learning phenomena. Previous empirical findings suggest that such a model must address three issues: First, affective and motivational reactions to errors, as well as cognitive and behavioural reactions specifically adjusted to the error in question have to be included (Dresel, Schober, Ziegler, Grassinger, & Steuer, 2013; Tulis, Grassinger, & Dresel, 2011). Secondly, such a theory must take into account critical characteristics of error-situations and indicate how these characteristics affect the potential contribution of individual dispositions, orientations, abilities or skills and current motivational states to adaptive learning behaviour. Finally an integrated framework must consider the effects of interactions between personal determinants, contextual conditions, and situational processes. Prior research and working models have tended to focus either on personal preconditions or the context, depending on the researcher’s primary concern. We attempt to overcome these existing shortcomings and to expand previous approaches by providing a framework which integrates proven theories of self-regulation, volition, motivation, emotion, and cognition.

2. Individual reactions to and learning from errors: A process model

The purpose of this section is to introduce a framework that includes the above presented theoretical perspectives and to provide a model which can provide an explanation of individual differences, situational influences and sequenced processes following error-experiences as antecedents for successful learning from errors (see Figure 1). Learning from errors is an effortful activity. Our understanding of learning from errors includes a detailed analysis of the error causes in order to identify and explain potential misconceptions, a self-evaluation of the underlying knowledge and its modification, as well as the correction of the error in question (e.g. Dresel, et al., 2013). Prior to these metacognitions and cognitive activities, learners have to deal with changes in affect and motivation after the perception of an unintended discrepancy between a current state and a desired outcome or a given standard.

More specifically, the perception of an error represents the (“bottom-up”) starting point in our model (see “*Error feedback/Detection of an error*” marked with an asterisk in Figure 1) which induces a sequence of processes (indicated with bold arrows in Figure 1). Yet irrespective of the type of error or its causes, this is assumed to trigger direct reactions in terms of affect based on primary appraisals of the situation (see “*Direct reactions towards errors*” in Figure 1). In line with Lazarus (1991), primary appraisals are directed towards the assessment of the relevance of this unintended discrepancy/goal incongruence to the learner and subsequent affect acts as a signal for this personally relevant deviation from an implicit or explicit standard. Based on these primary appraisals, different emotions such as surprise, frustration, anger or boredom may be



experienced. For example, a self-confident, high achieving learner may first experience surprise after error feedback, whereas a low achiever may experience frustration at first sight of an error—in the event that both learners value the task and aim to master the task. This first emotional reaction might be vague, maybe not as easy to categorize as a specific emotion, but in any case we would expect an observable change in arousal. We assume that primary reactions are followed by more indirect reactions towards the error at hand (see “*Indirect/Secondary reactions towards errors*” in Figure 1) including secondary appraisals directed at the assessment of controllability and personal resources to deal with the error (cf. Lazarus, 1991). It is further assumed that these secondary appraisal processes change or intensify the primary emotional reaction and the learners’ subsequent motivation. Analogous to top-down processing (i.e. knowledge or expectations are used to guide processing), further self- and task related appraisals, such as causal attributions (Weiner, 1986) are made. These, in turn, might evoke attribution-dependent emotions other than the learner’s primary emotional states—or the learner’s primary emotional states might be intensified. It can be expected that not all types of errors lead to the same processes and subsequent learning. For example, in contrast to careless mistakes (e.g. slips, caused by attentional problems, or lapses, caused by memory failures) only knowledge- and rule-based errors might bear a potential for learning (for this taxonomy see Reason, 1990). The nature of emotional and motivational changes is likely affected by the type of the error at hand. Thus, at this stage of the model, we presume that the error-type has an impact on the learners’ secondary appraisals, the subsequent self- and task-related motivation, and the respective learning actions.

In the next step (see “*Emotional and motivational regulation*” in Figure 1), these changes in self- and task-related motivation—and emotional states—are assumed to trigger emotional and motivational regulation processes (cf. Boekaerts, 2003). Depending on personal characteristics of the learner, these error-related regulation processes may become necessary to maintain learning motivation. For example, over-thinking the value of the task, the use of social resources, efficacy self-talk, or cognitive reappraisal may help to reassure the learner to proceed with the task despite setbacks (e.g. Wolters, 2003). Some learners may be more concerned with emotion-focused coping (Lazarus, 1993) to avoid a threat to self-worth and restore their well-being (cf. “well-being pathway”, Boekaerts, 2006), others may focus on strategies to re-direct attention and learning activities in order to master the task (Boekaerts, 2006; Kuhl, 2000). Hence, we assume that learners actively (i.e. consciously or automated) use emotional and motivational regulation strategies following errors to activate and sustain their cognitive, metacognitive and affective functioning (Butler & Winne, 1995; Wolters, 2003). We presume that adaptive (and effective) emotional and motivational self-regulation (Gross, 1998; Schwingen, Steinmayr & Spinath, 2009; Wolters, 1998) provides the basis for the use of appropriate metacognitive activities, cognitive strategies and learning behaviour to adequately reflect on the underlying misconception (subsumed under “*Learning process*” in Figure 1). However, the regulation strategies that learners may use can also be dysfunctional: The use of maladaptive strategies following errors, such as distraction, suppression or rumination (e.g. Gross, 1998; Knollmann, 2006) may impede a detailed self-explanation of errors and their respective correct counterparts. Furthermore, it can be assumed that—as for the use of learning strategies—some regulation strategies may be appropriate for certain learning contexts whereas the same strategies might be dysfunctional in other contexts (Engelschalk, Steuer & Dresel, 2015). In any case, inappropriate or failed regulation strategy use may result in the experience of negative deactivating emotions, such as hopelessness or boredom, which are held to be detrimental for motivation (e.g. Pekrun, Goetz, Daniels, Stupnisky, & Perry, 2010). Thus, emotions are not only assumed to act as a signal after the perception of a discrepancy, but they are also assumed to be an indicator of the learners’ current motivation. Consequently, they guide subsequent learning behaviour (e.g. in terms of persistence, attention focus, or information seeking) and they serve as a monitoring instrument for goal pursuit (Carver & Scheier, 1990). Hence, emotions are assumed to moderate learning processes and we regard the presence of activating (or epistemic) emotions as a necessary condition for persistent task engagement in the face of obstacles and for learning from errors in general.

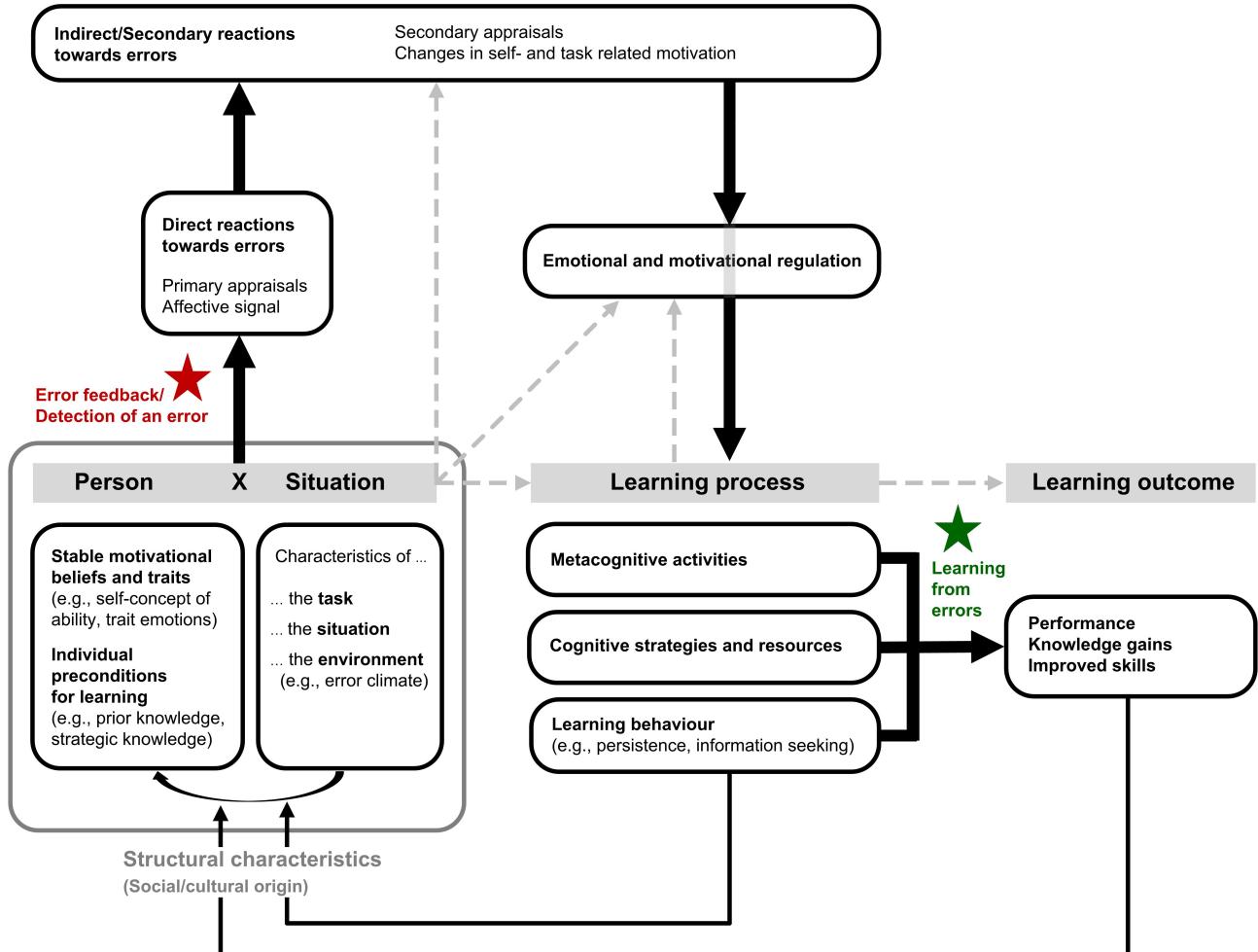


Figure 1. Process model of individual reactions to and learning from errors.

It is important to note that individuals' learning behaviour following errors, their emotional and motivational experiences and regulation strategies, and their subsequent metacognitions and cognitive activities are all assumed to be influenced by personal characteristics as well as contextual features which interact continuously with one another throughout the entire learning process. Learners continuously appraise the learning conditions against the background of their individual dispositions, skills and abilities (e.g. prior knowledge or topic-interest), and their motivational beliefs such as self-concept of ability or goal orientation (for an overview see Schunk, Meece & Pintrich, 2013). Previous findings indicate that the effectiveness of error encouragement training might depend on such individual differences (e.g. Gully et al., 2002). Contextual conditions include characteristics of the task (e.g. an enquiry-based learning task versus a routine task), the learning context (e.g. practice versus testing situation), and the interpersonal aspect of dealing with errors in social learning environments which may facilitate or impede learning from errors (i.e. error climate). Although located at the starting point in our model, personal and contextual conditions impact later processes as well (indicated with dashed arrows in Figure 1). Their interaction is affected by previous learning experiences and outcomes which are integrated in a broader social and cultural context. "*Learning from errors*" (marked with an asterisk in Figure 1) takes place in terms of reflection and self-explanation processes based on respective metacognitive activities, the use of appropriate cognitive strategies, and learning behaviour adapted to the new situation (see "*Learning process*" in Figure 1). Finally, this should result in the modification of the underlying knowledge, improved skills and performance gains (see "*Learning outcome*" in Figure 1) which are expected to have reciprocal effects on the learners' personal



conditions, and hence on the interpretation of subsequent error-situations (indicated with backwards directed arrows in Figure 1).

In order to validate the proposed processes, different stages/components of the model and their relations or sequenced effects need to be analysed: In particular, (1) the impact and interplay between different personal and situational conditions on individual reactions to errors and the use of error-specific adaptive regulation strategies, (2) the proposed changes in motivation and emotion and their function for further self-regulation and learning behaviour, (3) the relevance of metacognitive and cognitive activities for error-related learning processes, and (4) the necessity of affective-motivational functioning to provide a basis for such activities.

3. Empirical evidence and open research questions

So far we have provided some evidence for the assumed functions of emotions at the stage pertaining to direct/primary and indirect/secondary reactions towards errors, the use of error-related regulation strategies, and the influence of selected personal conditions and contextual factors on individual responses to errors (Dresel, et al., 2013; Steuer et al., 2013; Tulis, 2013; Tulis & Ainley, 2011; Tulis & Dresel, 2013; Tulis & Fulmer, 2013; Tulis et al., 2011; Tulis et al., subm.). In the present section we summarise the findings of three studies with different foci, namely individual determinants of adaptive dealing with errors (Study 1), motivational (self-regulation) processes following errors and their impact on subsequent learning behaviour (Study 2), and the dimensions of error climate and their impact on students' responses to errors (Study 3).

Study 1—located in the “*Person × Situation*” part of Figure 1—focused on individual components that may facilitate a learner's adaptive reaction to errors (Tulis et al., subm.). Previous studies (e.g. Dresel et al., 2013; Tulis & Ainley, 2011; Tulis et al., 2011) have already demonstrated a positive relationship between students' (more stable) motivational orientations (i.e. positive self-concept of ability, mastery goal orientation, adaptive error-related beliefs) and emotional/motivational reactions following errors. Based on these results Tulis et al. (subm.) tested a tripartite classification of adaptive individual dealing with errors in terms of a cognitive, an affective, and a behavioural component. More specifically, the authors analysed the distinctiveness of 614 students' self-reported beliefs about errors as learning opportunities from students' affective-motivational reaction tendencies that facilitate persistence and engagement despite setbacks, and students' behavioural reaction tendencies including metacognitive activities and error-related learning behaviour (Dresel et al., 2013). The results—obtained with confirmatory factor analyses demonstrating a good fit to the data—provided evidence for three distinct factors. In addition, the authors analysed their relationship to other motivational beliefs, and, whether these components of adaptive individual dealing with errors may differ between the scholastic domains of mathematics, English and German. Correlational findings suggested domain-specificity for the three components. Thus, error-related beliefs, habitualised affective-motivational and behavioural responses to errors might be acquired domain-specifically. Further research is needed before any conclusions can be drawn, but the results point to the likelihood that students' dealing with errors may not be differentiated along the verbal and mathematics continuum as, for instance, the academic self-concept is (e.g. Marsh, Walker & Debus, 1991). Furthermore, the findings emphasise the differentiation of personal conditions in terms of rather proximal beliefs in addition to less error-specific motivational beliefs, such as mastery goal orientation.

Study 2 (Tulis & Dresel, 2013, August) addressed motivational changes (see “*Emotional and motivational regulation*” in Figure 1), undergraduate students' motivational and emotional self-regulation following errors and its effects on learning behaviour (see “*Learning process*” in Figure 1) in a computer-based learning setting. Data were collected during two time intervals—the same study design was implemented in both studies with the only difference that in Study 2a, we additionally conducted stimulated



recall interviews immediately after the learning session to examine participants' use of various emotional and motivational regulation strategies following errors whereas -self-reported regulation strategies were assessed on-task after error feedback in Study 2b. Regarding the hypothesised motivational changes after making errors measured with on-task state items, we found a substantial decrease in students' motivation. Repeated-measures MANOVAs with the three components of adaptive individual dealing with errors (high versus low levels) as between-subject factors indicated a stronger decline in task-related motivation, situational interest and enjoyment, and perceived competence for students' low in action adaptivity, affective motivational adaptivity, and adaptive beliefs about errors, respectively. Interview data pointed out a rich variety of different emotional and motivational regulation strategies that are used following errors, ranging from "proximal goal setting", and the "use of social resources" (i.e. asking someone for help; most reported) to "self consequating" (i.e. motivating oneself by self-reinforcement for having reached a particular goal; least reported). In addition, also maladaptive strategies, such as "rumination" and "suppression" were reported in Study 2a. However, when measured on-task (Study 2b)—immediately after error feedback—appraisal based strategies, such as cognitive reappraisal (i.e., having a positive view on making errors as a natural part of learning) and mastery self-talk (i.e., thinking of the potential of errors for personal improvement) were more prominent, as was the use of maladaptive strategies. Thus, according to our model, a decrease in student motivation triggered the use of emotional and motivational regulation strategies, and personal characteristics served as a buffer. Regression analyses further emphasized differential associations between these strategies and adaptive learning activities after error feedback: Mastery self-talk and reappraisal were found to facilitate an in-depth analysis of the error at hand, whereas distraction negatively predicted the reflection of the underlying misconceptions. Logistic regression results indicated positive associations between proximal goal setting and students' actual persistence. In summary, our findings emphasised the importance of motivational self-regulation for subsequent engagement following errors, and hence the proposed function of emotional and motivational regulation strategies for subsequent learning processes and learning behaviour. Furthermore, they provided first evidence for a differentiation between adaptive and maladaptive error-related strategies.

The findings of Study 3 (Steuer et al., 2013) are based on a questionnaire-study with 1,116 students from 56 sixth and seventh grade classrooms. This study focused on contextual conditions and it is located in the "*Person × Situation*" part as well as related to the dashed arrows of Figure 1 that indicate the influence of characteristics of the learning environment on individual learning behaviour. Study 3 provided evidence for eight theoretically and empirically distinguishable subdimensions of error climate and their impact on students' individual dealing with errors. Steuer et al. (2013) further demonstrated that classroom error climate has an impact on students' affective-motivational and action adaptivity of error reactions, which, in turn, were positively associated with students' self-reported effort. Hence, according to our proposed model, the results supported the assumed association between personal conditions and characteristics of the social learning environment as well as their influences on individual learning behaviour following errors.

4. Contribution to theory development and implications for future research

Taken together, our findings corroborate the assumed interplay between personal and contextual conditions as well as the importance of functional emotional and motivational self-regulation for adaptive dealing with errors. Supported by some preliminary empirical evidence, the proposed model provides a more complete understanding of the motivational processes following errors in interaction with personal and contextual conditions. It gives several indications of how learners' adaptive reactions to errors—a necessary precondition for learning from errors—can be supported. However, besides motivational processes, further research is needed to address the cognitive processes specifically related to effective learning from errors (see "*Learning process*" in Figure 1). Research findings on conceptual change, cognitive conflicts, impasse driven learning and productive failure may provide the basis for further investigations using on-task



measurements (e.g. eye-tracking). Another important issue raised by previous findings (e.g. Keith & Frese, 2005) concerns metacognitive activities—also part of the proposed framework that needs to be specified in future research. Finally, our findings raised some methodological issues for future research: Retrospective measurements (even if the time interval is short) might not offer adequate insights into actual and transient task-specific regulation processes, especially strategies involving cognitive change. Therefore, future studies should differentiate between strategies learners *tend* to use to regulate their motivation during learning (e.g. assessed with questionnaires) and the actual strategy learners use (measured on-task).

In summary, our model contributes to current research on motivation in several ways: (1) it expands current theories of self-regulated learning because it highlights perceived errors as initiating points for self-regulatory processes, (2) it provides a solid foundation for the analysis of motivational processes compatible with almost all contemporary theories of motivation, and (3) it enables the examination of personal, contextual and situational conditions and their interactions as well as their potential impact on error-related learning processes. Finally, our proposed model provides a unified framework specifically adjusted to the phenomenon of *learning from errors*—a growing but still barely investigated field of educational research. Previous findings and future research can be easily integrated into the present framework in order to specify the antecedents and processes of effective learning from errors. Finally, the major implication for the future research practice is the process-related view on learning.

Keypoints

- A theoretical framework specifically adjusted to the phenomenon of *learning from errors* is introduced.
- Changes in motivation trigger emotional and motivational self-regulation processes.
- Individual differences are explained by personal and situational conditions, emotional, motivational, metacognitive and cognitive processes.
- Contemporary theories of motivation are integrated in the model.
- Antecedents and processes of successful learning from errors are specified.

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